Amplification of the induced ferromagnetism in diluted magnetic semiconductor

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Magnetic properties of the planar structure consisting of a ferromagnetic metal and the diluted magnetic semiconductor are considered (by the example of the structure Fe/Ga(Mn)As, experimentally studied in [1]). In the framework of the mean field theory, we demonstrate the presence of the significant amplification of the ferromagnetism, induced by the ferromagnetic metal in the near-interface semiconductor area, due to the indirect interaction of magnetic impurities. This results in the substantial expansion of the temperature range where the magnetization in the boundary semiconductor region exists, that might be important for possible practical applications.

Introduction

One of the major roadblocks on the way to developing the semiconductor spintronics is now the lack of semiconductor materials and structures that would be ferromagnetic at the room temperature. Today, the record value of the Curie temperature is reached with the diluted magnetic semiconductor $Ga_{1-x}Mn_xAs$ ($x = 0.05 - 0.07$) and equals $T_C \approx 180$ K [2]. In this connection, the interest has been aroused in hybrid structures of the metal/semiconductor type whose magnetic properties are to the great extent defined by the high-temperature ferromagnetism of the metal being the part of the structure. For instance, in the recent paper [1] (selected for a Viewpoint in *Physics*) the planar structure $Fe/Ga_{1-x}Mn_xAs(100)$ has been investigated. It has been shown that the induced ferromagnetic state in the near-interface layer of the semiconductor film survives even at the room temperature. The magnetization of that semiconductor region is opposite (by the direction) to the magnetization of Fe-film, that suggests the antiferromagnetic exchange interaction between Fe atoms and impurity Mn atoms in GaAs matrix. The intensity of that interaction is determined by the relevant effective magnetic field H_{Fe} depending on the mutual disposition of a given Mn atom and different Fe atoms interacting with the latter. In addition, there is the indirect exchange interaction of the ferromagnetic nature between Mn atoms putting into effect via mobile charge carriers (for example, by the RKKY mechanism). That interaction is characterized by the effective exchange field H_{Mn} depending on the distance r_k ($k = 1, 2, \ldots$) between a given Mn atom and different Mn atoms interacting with the latter. Therewith, it is essential that the carrier mobility in the diluted magnetic semiconductor is so low (on the order of 10 $cm^2/V{\cdot}c$ [3, 4]) that due to the collision broadening of the hole energy levels the system becomes to be effectively three-dimensional and there is no need to take into account any effect of the size quantization [5].

We show that the interference of both mentioned interactions, responsible for the magnetic ordering of Mn atoms, multiplies the effect of each mechanisms severally. In fact, the magnetic seeding which is the spin polarization of semiconductor magnetic atoms, induced by the ferromagnet, is significantly amplified due to the indirect interaction between those atoms. As a result, the Curie temperature, determining the existence of the ferromagnetism in the boundary region of the magnetic semiconductor increases essentially.

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Mean field approach

The magnetization in the boundary layer of the diluted magnetic semiconductor is parallel to the interface plane and significantly non-uniform along the direction perpendicular to the latter (z-axis). It is convenient to characterize such a non-uniform magnetization by the reduced local magnetization $-1 \leqslant j(h) \equiv M(h)/M_s \leqslant 1$ (h is the distance from the interface plane, M_s is the saturation magnetization). In the framework of the mean field theory, it is defined by the equation

$$j(h) = \tanh\left[\frac{\mu H_{\text{eff}}(h)}{kT}\right], \tag{1}$$

where μ is the magnetic moment of the impurity Mn atom,

$$H_{\text{eff}}(z) = \sum_i H_{\text{Fe}}(\mathbf{R}_i) + \sum_k H_{\text{Mn}}(r_k) \tag{2}$$

is the total effective field effecting on a given Mn atom. Summation is performed (in the first sum) over all Fe atoms, and (in the second sum) over all Mn atoms.

When calculating the first sum in (2) one should take into account that considered Fe and Mn atoms are, in general, situated in media with different exchange interaction lengths. Hence, the result of that interaction is not a simple function of the distance R_i between those atoms. However, lest the calculation be complicated by unprincipled details, we proceed below from the simple exponential spatial dependence of the form

$$\mu H_{\text{Fe}}(R_i) = j_{\text{Fe}}(\mathbf{R}_i) J_{\text{Fe}} \exp[-R_i/\ell_{\text{Fe}}], \tag{3}$$

where J_{Fe} and ℓ_{Fe} are, accordingly, the characteristic energy and the length of the interaction, $j_{\text{Fe}}(\mathbf{R}_i)$ is the local magnetization of the Fe film in the point of the relevant Fe atom location. Choosing the coordinate origin in the interface plane, assume Fe layer being disposed in the region $-L_{\text{Fe}} < z < 0$, and the semiconductor film is in the interval $0 < z < L_{\text{Mn}}$. Then, in the continual approximation

$$\sum_i \mu H_{\text{Fe}}(R_i) = J_{\text{Fe}}\, n_{\text{Fe}} \int\limits_{z=-L_{\text{Fe}}}^{0} \int\limits_{\rho=0}^{\infty} j_{\text{Fe}}(z) \exp\left[-\sqrt{\rho^2 + (h-z)^2}/\ell_{\text{Fe}}\right] 2\pi\rho d\rho dz, \tag{4}$$

where n_{Fe} is the concentration of Fe atoms. In principle, the magnetization j_{Fe} depends on the temperature, however if the latter is significantly lower than the ferromagnetic Curie temperature and the film itself is in the single-domain state, then $j_{\text{Fe}}(z) \equiv 1$, and it follows from (4)

$$\sum_i \mu H_{\text{Fe}}(R_i) = 4\pi n_{\text{Fe}} \ell_{\text{Fe}}^3 J_{\text{Fe}} \Phi(h), \quad \Phi(h) = e^{-h/\ell_{\text{Fe}}}\left[1 + \frac{h}{2\ell_{\text{Fe}}} - \left(1 + \frac{L_{\text{Fe}} + h}{2\ell_{\text{Fe}}}\right) e^{-L_{\text{Fe}}/\ell_{\text{Fe}}}\right]. \tag{5}$$

Before calculating the second sum in (2) it should be noted there is no complete understanding the nature of the ferromagnetism in diluted magnetic semiconductors so far. Among mechanisms leading to the ferromagnetic ordering of magnetic impurity spins various forms of their indirect interaction, induced by mobile charge carriers, are considered: RKKY-exchange [6], kinematic exchange [7, 8], etc. [7]. In addition, there is the universal Bloembergen-Rowland

mechanism [9], which does not require the presence of mobile charge carriers (or their high concentration leading to the carrier degeneration) and could be drew for describing ferromagnetism in systems of the Ga(Mn)As, Ga(Mn)N type [10]. The essence of that mechanism is the interaction of impurity spins via virtual holes appearing in the valence band on the transition of electrons from that band to acceptor levels. The energetic threshold of this process, concerned with the finite energy Δ of the acceptor ionization, results in the exponential decay of the relevant interaction with the inter-impurity distance. The characteristic length of the decay is defined by the de Broglie wave length $\lambda_\Delta = \hbar(2m\Delta)^{-1/2}$ of holes with the energy Δ and the mass m. The expression for the effective exchange field $H_{\rm eff}$ of the indirect interaction of two parallel impurity spins separated by the distance r reads [10]

$$\mu H_{\rm eff}(r) = -\frac{J_{pd}^2 m^2 \Delta}{\pi^3 \hbar^4 N^2 r^2} K_2(2r/\lambda_\Delta), \tag{6}$$

where J_{pd} is the energy of the contact interaction of the impurity spin with a hole, N is the concentration of matrix atoms, K_2 is the McDonald function. For long distances ($r \gtrsim \lambda_\Delta/2$), $K_2(2r/\lambda_\Delta) \approx (4r/\pi\lambda_\Delta)^{-1/2} \exp(-2r/\lambda_\Delta)$ asymptotically. Keeping for that case in (6) the most essential exponential part of the interaction spatial dependence only, one writes it in the form

$$\mu H_{\rm eff}(r) = -J_0 \exp(-r/\ell), \tag{7}$$

$\ell = \lambda_\Delta/2$, $J_0 \sim J_{pd}^2/8\pi^3 \Delta N \lambda_\Delta^3$.

Similar expression for the energy of the magnetic impurity interaction is exploited when investigating the kinematic exchange model [7]. At last, if one turns to the RKKY interaction, under the strong scattering of carriers (see above) its intensity drops with the distance so rapidly that one could neglect the alternating-sign nature of that interaction and describe it by means the main exponential factor of the form $\exp(-r/\ell)$ (ℓ is the length of the spin coherency).

In the light of the above-stated we use the following model relation for the indirect interaction of a given Mn atom with another Mn atom situated in the point with the local magnetization equal to $j(z_k)$:

$$\mu H_{\rm Mn}(r_k, z_k) = j(z_k) J_{\rm Mn} \exp[-r_k/\ell_{\rm Mn}]. \tag{8}$$

Here $J_{\rm Mn}$ and $\ell_{\rm Mn}$ are, accordingly, the characteristic energy and the length of the indirect interaction. In the continual approximation,

$$\sum_k \mu H_{\rm Mn}(r_k, z_k) = J_{\rm Mn}\, n_{\rm Mn} \int_{z=0}^{L_{\rm Mn}} \int_{\rho=0}^{\infty} j(z) \exp\left[-\sqrt{\rho^2 + (h-z)^2}/\ell_{\rm Mn}\right] 2\pi\rho d\rho dz =$$

$$= 2\pi n_{\rm Mn} \ell_{\rm Mn}^3 J_{\rm Mn} \int_0^{L_{\rm Mn}} K(z,h) j(z) dz, \tag{9}$$

where $n_{\rm Mn}$ is the concentration of Mn atoms,

$$K(z,h) = \left(1 + \frac{|h-z|}{\ell_{\rm Mn}}\right) \frac{e^{-|h-z|/\ell_{\rm Mn}}}{\ell_{\rm Mn}}. \tag{10}$$

Unlike the infinite system, the value of the integral (9) depends on the coordinate h of chosen point.

The mean field equation (1) could be now written in the form

$$j(h) = \tanh\left[\frac{1}{\tau}\left(c_{\rm Fe}\Phi(h) + c_{\rm Mn}\int\limits_0^{L_{\rm Mn}} K(z,h)j(z)dz\right)\right], \qquad (11)$$

where $c_{\rm Fe} = 4\pi n_{\rm Fe}\ell_{\rm Fe}^3(J_{\rm Fe}/J_{\rm Mn})$, $c_{\rm Mn} = 2\pi n_{\rm Mn}\ell_{\rm Mn}^3$ are structure parameters, $\tau = kT/J_{\rm Mn}$ is the reduced temperature. That is the non-linear integral equation determining the profile and the temperature dependence of the magnetization in the semiconductor part of the structure. It is non-local: the magnetization $j(h)$ is defined by all points $(0 < z < L)$ of the Ga(Mn)As film.

Results

Numerical solution of Eq. (11) has been found, in the same way as in [5], by the successive-approximation method. Though we have kept in mind the concrete structure Fe/$Ga_{1-x}Mn_xAs$ [1], the qualitative character of our examination makes using exact values of parameters, governing the system behavior, to be surplus. Therefore, we accept that the constant a of the (face centered cubic) Fe lattice is about half as the constant of the (body centered cubic) sublattice of Ga atoms (which are replaced by Mn atoms) and set $n_{\rm Fe}a^3 = 2$, $n_{\rm Mn}a^3 = 0.05$ (that corresponds to $x \approx 0.1$), and for other parameters accept the values $L_{\rm Fe} = L_{\rm Mn} = 7a$ [1], $\ell_{\rm Fe} = a$, $\ell_{\rm Mn} = 1.5a$. As for the ratio $J_{\rm Fe}/J_{\rm Mn}$, it has been varied over a wide range (see below).

Putting $c_{\rm Fe} = 0$ in (11), one could find the temperature interval of the intrinsic (non-induced by the Fe film) ferromagnetism in Ga(Mn)As. The relevant Curie temperature occurs to be equal $\tau_{\rm C} \approx 5$, or $kT_{\rm C} = 5J_{\rm Mn}$ (see below Fig. 2). For that case, in Fig. 1 (left panel, curve Mn↔Mn) the spatial distribution $j_{\rm Mn}(z)$ of the local Mn magnetization at the temperature $\tau = 4 < \tau_{\rm C}$ is shown. As one would expect, it is symmetric about the middle plane ($z = L/2$) of the semiconductor layer. In the same Fig. 1, one could see the spatial magnetization distribution of Mn atoms, induced by the their exchange interaction with Fe atoms only, without intrinsic indirect interaction (left panel, curve Mn↔Fe) for $J_{\rm Fe}/J_{\rm Mn} = 2.5$. Such an induced magnetization drops rapidly with moving away from the interface boundary Fe/Ga(Mn)As ($z = 0$). At last, the third curve (Mn↔Mn+Mn↔Fe) in the left panel of Fig. 1 is the result of the combined action of both mechanisms of magnetic ordering manifesting in the high amplification of the induced ferromagnetism by the indirect interaction of magnetic Mn impurities. The respective magnetization gain is especially high away from the boundary Fe/Ga(Mn)As ($z \gtrsim L/2$), where the induced magnetization is enlarged up to fivefold value.

It is remarkable that the substantial amplification of the induced magnetization remains even at temperatures being much higher the Curie temperature corresponding to the intrinsic ferromagnetism of Ga(Mn)As. The middle panel in Fig. 1, referring to the temperature $\tau = 6 > \tau_{\rm C}$, demonstrates that the gain of the induced ferromagnetism even in this case remains equally high, though away from the interface the absolute value of the magnetization drops somehow.

The magnetization gain in magnetic semiconductor stimulated by the spatially localized magnetic seeding is obviously demonstrated in the right panel of Fig. 1, where as the spatial dependence of the effective exchange interaction of Fe and Mn atoms we have chosen the linear approximation $\Phi(0) + \Phi'(0)h = 1 - h/2\ell_{\rm Fe}$ of the function (5) (different from zero in the range

$0 < h < 2\ell_{\rm Fe}$ only). It is seen that even at the temperature $\tau = 6$, which is essentially exceeds the Curie temperature $\tau_{\rm C} \approx 4$, magnetic ordering appears even in that region of the magnetic semiconductor where the induced seed magnetization is absent.

It is convenient to characterize the non-uniformly magnetized layer Ga(Mn)As by the average magnetization

$$\langle j_{\rm Mn} \rangle = \frac{1}{L} \int\limits_0^L j_{\rm Mn}(z) dz. \tag{12}$$

Temperature dependencies of that value for the intrinsic (Mn↔Mn), induced (Mn↔Fe) and amplified combined (Mn↔Mn+Mn↔Fe) ferromagnetism are shown in Fig. 2 (left panel: $\ell_{\rm Mn} = 1.5a$, $J_{\rm Fe}/J_{\rm Mn} = 0.5$, middle panel: $\ell_{\rm Mn} = 1.5a$; $J_{\rm Fe}/J_{\rm Mn} = 5$). It is seen that significant magnetization of Ga(Mn)As remains even at the temperature which is by six (and more) times higher than the intrinsic Curie temperature. Such a giant expansion of the temperature interval of existing the ferromagnetism near the interface Fe/Ga(Mn)As has been experimentally observed in [1].

The effect of amplifying the induced ferromagnetism in the considered system due to the indirect interaction of magnetic impurities in the semiconductor depends severely on the intensity $J_{\rm Fe}$ of the exchange interaction Mn↔Fe and temperature. Corresponding dependencies are shown in Fig. 3, wherefrom it is seen that though the maximum relative effect (defined by the ratio $(j_{\rm MM+MF} - j_{MF})/j_{\rm MF}$, where j_{MF}, $j_{\rm MM+MF}$ are magnetisations corresponding to Mn↔Fe and Mn↔Fe+Mn↔Mn curves) is observed at a temperature somewhat lower than the intrinsic Curie temperature (in the considered case, at $\tau \approx \tau_{\rm C} \approx 5$), the significant (and the most important) amplification effect remains even at much higher temperatures.

At last, notice that varying other system parameters does not lead to the qualitative modification of results, describing the properties of the considered system. For instance, three temperature dependencies $\langle j_{\rm Mn}(\tau) \rangle$ of the above-mentioned average magnetisations for the case $\ell_{\rm Mn} = 3a$, $J_{\rm Fe}/J_{\rm Mn} = 0.5$, shown in Fig. 1 (right panel), differ from the same dependencies for the case $\ell_{\rm Mn} = 1.5a$, $J_{\rm Fe}/J_{\rm Mn} = 0.5$ (see the left panel) mainly by the scale change. Conducted calculations demonstrate the stability of basic results relative to varying problem parameters.

Conclusions

Magnetic properties of the planar structure consisting of a ferromagnetic metal and the diluted magnetic semiconductor are considered (by the example of the structure Fe/Ga(Mn)As, experimentally studied in [1]). In the framework of the mean field theory, we demonstrate the presence of the significant amplification of the ferromagnetism, induced by the ferromagnetic metal in the near-interface semiconductor area, due to the indirect interaction of magnetic impurities. This results in the substantial expansion of the temperature range where the magnetization in the boundary semiconductor region exists – far beyond the limits of the interval limited from above by the Curie temperature of the magnetic semiconductor itself. Results might be used for describing properties of combined nanosized systems ferromagnetic/diluted magnetic semiconductor.

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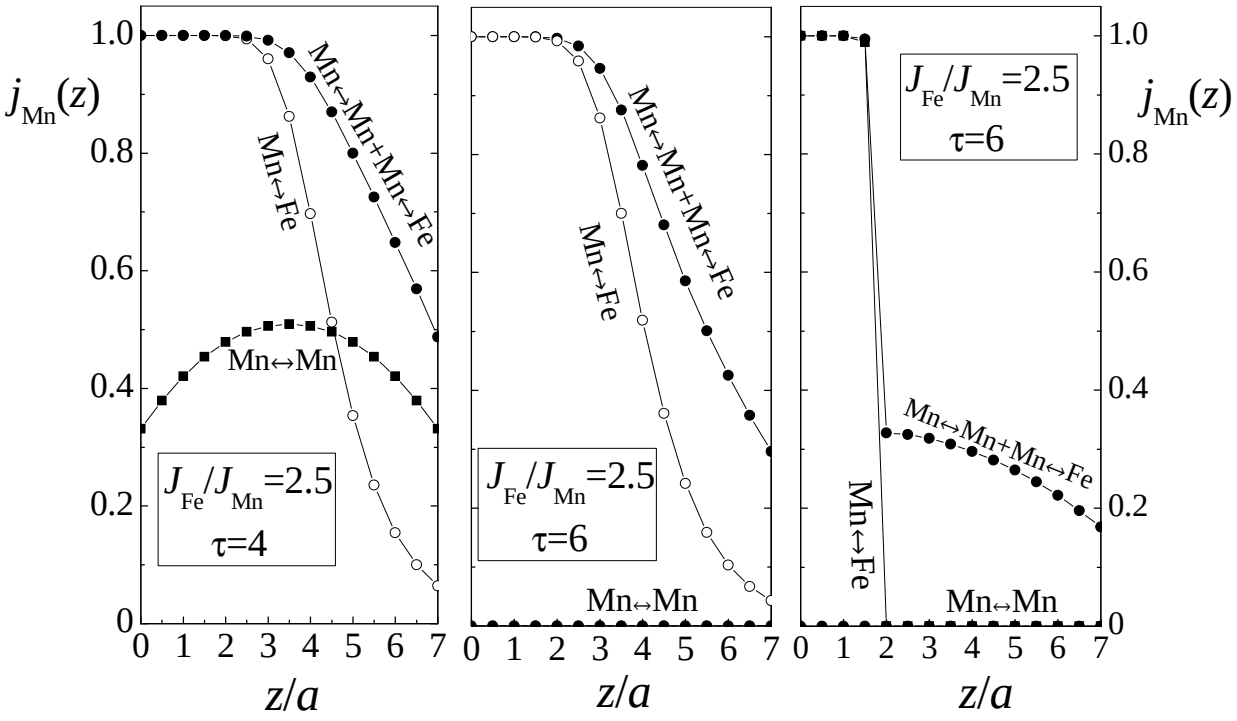
Figure captions

Fig. 1. Spatial distributions of the local semiconductor magnetization $j_{\rm Mn}(z)$ near the interface Fe/Ga(Mn)As at temperatures $\tau = 4 < \tau_{\rm C}$ (left panel) and $\tau = 6 > \tau_{\rm C}$ (middle and right panels) for $J_{\rm Fe}/J_{\rm Mn} = 2.5$. Mn↔Mn is the intrinsic magnetization of the semiconductor, Mn↔Fe is induced one, Mn↔Mn+Mn↔Fe is the induced magnetization amplified by the indirect interaction. The spatial dependence of the effective exchange interaction of Fe and Mn atoms: left and middle panels – Eq.(5), right panel – the linear approximation (see text).

Fig. 2. Temperature dependencies of the average magnetization $\langle j_{\rm Mn}\rangle$ for the intrinsic (Mn↔Mn), induced (Mn↔Fe) and amplified combined (Mn↔Mn+Mn↔Fe) ferromagnetism of the considered structure. Left panel: $\ell_{\rm Mn} = 1.5a$, $J_{\rm Fe}/J_{\rm Mn} = 0.5$, middle panel: $\ell_{\rm Mn} = 1.5a$, $J_{\rm Fe}/J_{\rm Mn} = 5$, right panel: $\ell_{\rm Mn} = 3a$, $J_{\rm Fe}/J_{\rm Mn} = 0.5$.

Fig. 3. Dependencies of the average magnetization $\langle j_{\rm Mn}\rangle$ for the induced (Mn↔Fe) and amplified combined (Mn↔Mn+Mn↔Fe) ferromagnetism of the considered structure on the exchange (Mn↔F) interaction energy $J_{\rm Fe}$ at the temperature $\tau = 6 > \tau_{\rm C}$. In the insert – temperature dependencies of the relative gain effect for the induced magnetization at various $J_{\rm Fe}$ values.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z/a
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Mn↔Mn+Mn↔Fe
Mn↔Mn
J_{Fe}/J_{Mn}=2.5
τ=4
J_{Fe}/J_{Mn}=2.5
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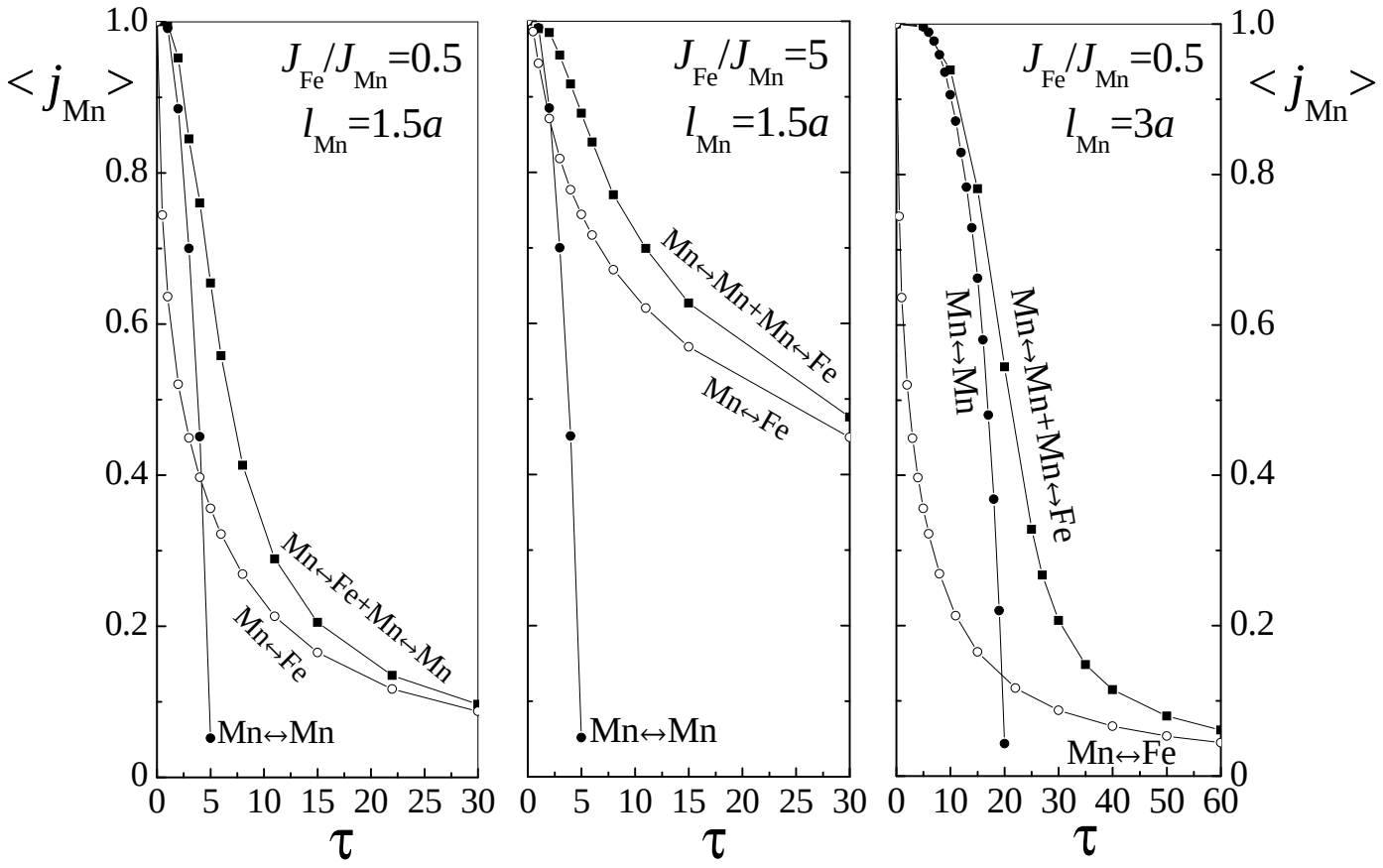
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l_{Mn}=1.5a
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Mn↔Mn
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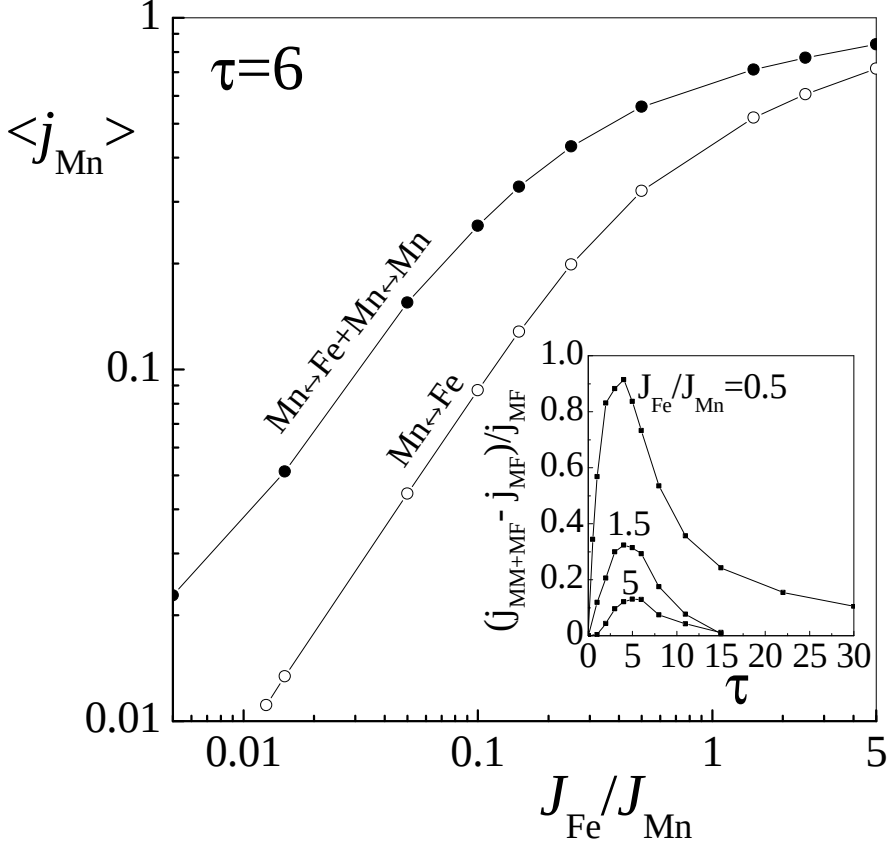
τ
τ
τ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J_Fe/J_Mn=0.5
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5
0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
25
30
τ